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THE INFLUENCE OF SUBSURFACE MOISTURE ON RILL SYSTEM EVOLUTION

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ABSTRACT

Rill development studies have focused almost exclusively on surface erosion processes and critical threshold hydraulic conditions. Characteristic rill features, such as arcuate headcuts and knickpoints, are morphologically similar to the 'theatre-headed' valleys which have been associated with 'sapping' processes at various scales. This paper reports on laboratory experiments designed to identify linkages between surface flow hydraulics, subsurface moisture conditions and rill development. Experiments were carried out in a 16·57 m^2 flume under simulated rainfall with soil samples up to 0·15 m depth in which moisture conditions were monitored by miniature time-domain reflectometer probes. Tests showed complex responses in which some rill incision reflected surface flow conditions, but major rill system development with markedly enhanced sediment yield was closely associated with high soil moisture contents. It was not possible to measure seepage forces directly, but calculation and observation indicate that these were less important than reduction in soil strength with saturation, which resulted in increased effective runoff erosivity. This caused concentrated undercutting along the water table at rill walls, while slightly stronger surface layers above the water table formed microscarps. These retreated along the water table into interrill surfaces, producing residual pediment transport slopes. The microscarps eventually disappeared when the water table reached the surface, eliminating differential soil strength.

The experiments showed complex relationships between surface and subsurface erosional processes in evolving rill systems, strongly influenced by soil moisture dynamics. The very small topographic and hydraulic head amplitudes indicate that seepage forces and 'sapping' were minimal. The dominant effect of soil moisture was reduction of soil strength with saturation, and increased runoff entrainment. Experimental conditions were not unusual, either for agricultural fields or natural hillslopes, and the intricate interrelationship of surface and subsurface erosion processes observed is probably not uncommon. Attempts to link specific morphologic features at rill scale to dominance of surface or subsurface processes alone are therefore unlikely to be successful or reliable.

KEY WORDS: rill system development; hydraulic thresholds; soil moisture; sapping; laboratory experiments.

INTRODUCTION

The geomorphological significance of rill systems has been recognized since Horton's (1945) paper on drainage system evolution and Schumm's (1956) use of rill-scale analogues in the Perth Amboy badlands as a basis for concepts of river channel development. Rills have also been a central focus in soil erosion research because of associated rapid increase in soil transport rates (e.g. Loch and Donnollan, 1983). Most rill studies have emphasized formation by surface processes, particularly thin sheetflow, and have attempted to isolate critical threshold values for diagnostic hydraulic parameters (Bryan, 1987). Subsurface process have usually been invoked only where micropiping occurs on swelling clay soils (e.g. Bryan *et al*., 1978; Gerits *et al*., 1987).

The diagnostic hydraulic parameters most frequently identified are shear velocity (u^*), stream power (ω) and Froude number (Fr) (e.g. Govers and Rauws, 1986; Rauws, 1987; Rauws and Govers, 1988; Bryan and Peosen, 1989; Govers *et al*., 1990; Rose *et al*., 1990; Slattery and Bryan, 1992a; Merz and Bryan, 1993). Virtually all studies concur that rill incision requires u^* values greater than about 0·035 m s^{-1}, but otherwise there is little

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agreement about the most useful parameters or critical threshold values. This may reflect differences in soils and experimental design, but comparison of results is also hindered by lack of data on soil conditions (e.g. bulk density, antecedent moisture) and common morphological criteria.

Merritt (1984) and Torri *et al*. (1987) suggested explicit criteria to identify 'microrill' incision linked with gently sloping headcuts formed by flow convergence. In many studies, however, till incision is associated with steep or vertical, arcuate headcuts, which dramatically alter local hydraulic conditions (Bryan, 1990). Ephemeral arcuate knickpoints can develop within rill channels (Bryan and Poesen, 1989), but more persistent features form as headcuts incised into more resistant surface layers. These are perfect small-scale analogues of gullies (Bryan and Oostwoud Wijdenes, 1992) and of large river channels in bedrock, as recognized in DePloey's (1989) model.

The arcuate headcuts described were attributed to surface erosion processes. However, this typical morphology closely resembles the 'theatre-headed' valleys often linked to subsurface sapping or seepage (e.g. Hinds, 1925; Higgins, 1974, 1982, 1990; Kochel *et al*., 1985; Baker, 1990; Onda, 1994; Uchupi and Oldale, 1994; Nash, 1996). Some observations involve large valleys related to groundwater weathering in resistant rock (Laity, 1983; Laity and Malin, 1985; Kochel and Piper, 1986; Howard and McLane, 1988), and others concern small-scale features in laboratory studies with low cohesion materials (Howard and McLane, 1988; Sakuro *et al*., 1987; Gomez and Mullen, 1992).

This brief literature review suggests that drainage systems with arcuate headcuts, steep sides and broad flat floors can be formed at various scales by either surface or subsurface processes. This is potentially significant as they have been used as evidence of processes which cannot be directly observed, as with suggested sapping features on Mars (Higgins, 1982; Kochel *et al*., 1985). More precise understanding of the relationships between channel and basin form, and surface and subsurface erosion processes is therefore necessary. It is difficult to test these relationships at large scale, but it is possible at laboratory scale. However, few laboratory studies provide simultaneous information on both surface and subsurface processes. Experimental design in most of the laboratory rill studies identified above would certainly have involved significantly impeded drainage, yet only surface process data are available. In addition, in most cases, data were collected only at terminal weirs, so that precise identification of entrainment processes is very difficult.

This paper describes experiments carried out at the Soil Erosion Laboratory, University of Toronto, designed to provide:

1. observations of rill system development patterns;
2. simultaneous local measurement of surface hydraulic and soil moisture data, together with water and sediment discharge at a terminal weir;

with two objectives:

1. to identify the nature of subsurface erosion processes active in rill development on soils;
2. to determine if surface or subsurface processes can be linked with specific morphological characteristics (e.g. 'theatre-valley' morphologies) at rill scale.

EXPERIMENTAL DESIGN

Experiments were carried out in a planar flume (7·1 m × 2·4 m) with a surface area of 16·57 m^2 and inclination of 0·087. The base was formed with mesh inserts covered by porous fabric intended to provide free drainage, but which turned out to be somewhat impermeable. A mixture of two soils from southern Ontario, the Pontypool sand and Peel clay, was used in a 4:1 ratio. This mixture has been used in several previous studies (Bryan and Poesen, 1989; Bryan, 1990; Slattery and Bryan, 1992a,b, 1994) providing abundant background information on material behaviour and rill initiation under different experimental conditions. Sample characteristics are shown in Table I.

Air-dry material was sieved through an 8 mm sieve, then packed into the flume to an average initial bulk density of 1·3 Mg m^{-3}. Soil was packed in several layers, each lightly raked to minimize heterogeneity and structural layering. Despite care, some heterogeneity did occur, but this was localized and random. The bed was

Table I. Characteristics of binary soil used in experiments

Characteristic	
Sand content (%)	49·4
Silt content (%)	32·5
Clay content (%)	18·1
D_{50} (mm)	0·25
D_{90} (mm)	2·00
Liquid limit (%)	17·1
Consistency ($c_{5\text{-}10}$) index (%)	1·67
WSA>2·8 mm (% weight)	1·91
WSA>0·5 mm (% weight)	8·12
Saturated hydraulic conductivity (m s^{-1})	0·0022

Table II. Summary data for three initial and two subsequent flume experiments

	Date of experiment				
	6 April	20 May	2 June	7 December	10 December
Duration (min	120	120	60	120	60
Antecedent moisture content ml ml^{-1})	0·085 8·5	0·055 5·5	0·13 13·0	0·049 4·9	0·194 19·4
Mean bulk density (Mg m^{-3})	1·3	1·3	1·5	1·3	1·5
Total rainfall (mm)	117·2	107·1	54·8	101·9	59·5
Mean rainfall intensity (mm h^{-1})	58·6	53·6	54·8	50·9	59·5
Storm discharge (m^3)	1·606	1·587	0·934	0·911	0·991
Peak discharge (1 min^{-1})	19·0	18·4	19·1	12·8	16·9
Runoff coefficient (%)	81·7	88·3	99·0	53·3	99·3
Storm sediment discharge (kg)	61·9	72·1	58·5	80·8	110·3
Peak sediment discharge (g l^{-1})	51·5	67·5	88·8	125·4	146·8

shaped to a broad central valley (to 6 m above the weir) to constrain rill development and facilitate instrumentation. Initial soil depths were 0·15 and 0·10 m at the drainage divide and central valley, respectively, providing an average initial interrill slope of 0·042 and thalweg of 0·087.

Tests were carried out with simulated rainfall generated by two SPRACO nozzles (#48252613) at 4 m mean fall-height. Rainfall was measured by eight manual gauges arranged around the flume edge (Table II). Rainfall distribution was generally satisfactory, but some concentration occurred in the upper flume and where spray cones overlapped in the central flume which could not be precisely defined with gauges confined to the periphery. Three initial experiments were carried out on newly sieved soil and two subsequent tests (2 June, 10 December) on pre-rilled surfaces. Initial tests lasted 120 min, and those on pre-rilled surfaces, 60 min.

Water and sediment discharge were measured at the weir at 5 min intervals after flow initiation. Data on local flow and sediment transport conditions (flow velocity, depth, width, suspended sediment concentration and bedload) were collected almost continuously by observers on mobile sampling bridges using techniques described by Bryan (1990). Flow data were used to calculate hydraulic variables. In initial tests, data were collected from the central valley and at most rill initiation locations, but in subsequent tests measurement was concentrated in a few selected rill channels.

Information on subsurface moisture conditions were collected from 14 miniature time-domain reflectometer (TDR) probes (Hawke, 1997). These were inserted vertically through the base of the flume at the locations shown in Figure 5b, and linked to a Tektronix cable tester and a Campbell data logger. The probes integrate moisture content over the 8 cm probe sensor length.

(a)

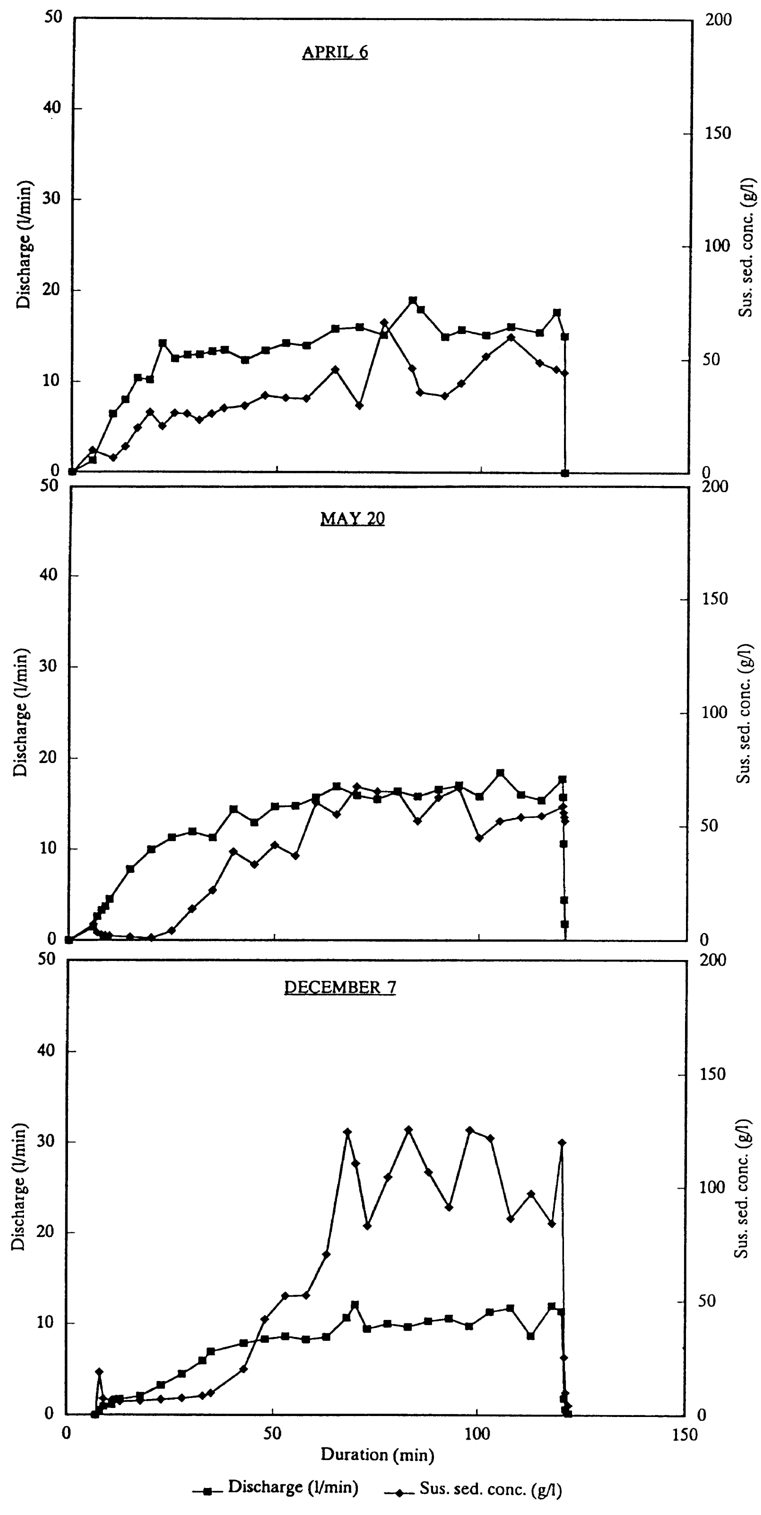
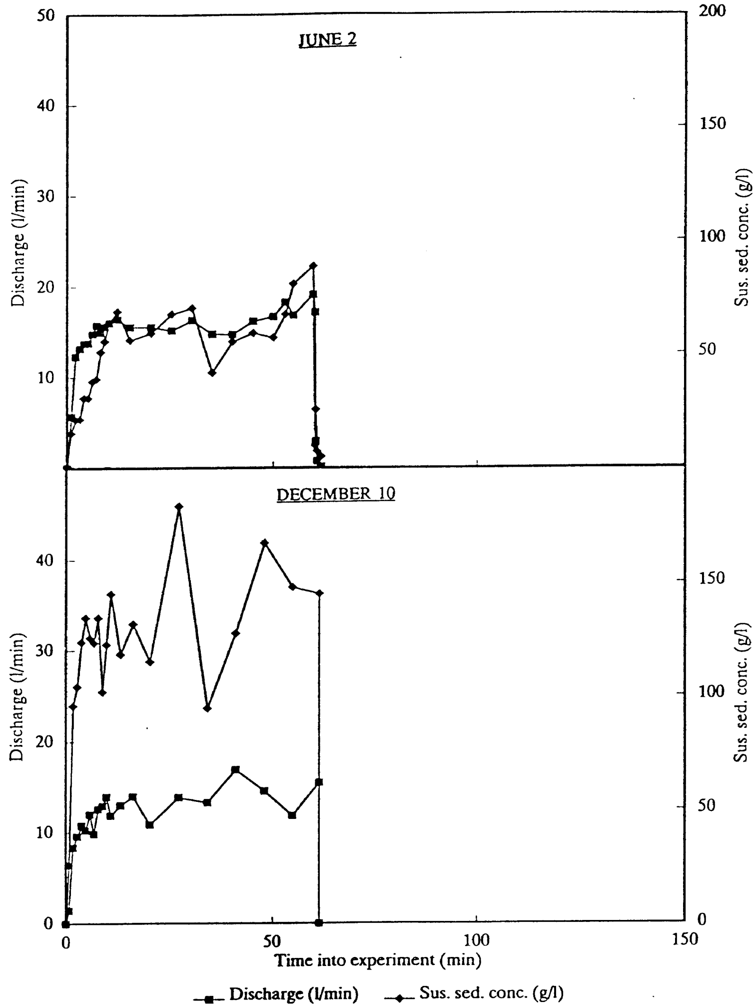


Figure 1. Hydrograph and sediment concentration variations: (a) during initial experiments on newly prepared soils, 6 April, 20 May, 7 December; (b) during subsequent experiments on rilled surfaces, 2 June, 10 December

(b)



Rill system initiation and evolution were reported individually by observers, and recorded by video cameras and by vertical and oblique air photos taken at 15 min intervals. Photos were used to plot progressive rill development maps.

RESULTS

Summary results are shown in Table II. Tests were carried out in two groups, in spring and winter. The intention was to use identical conditions, which was essentially achieved in the first test group. During the initial test in the winter set, antecedent moisture content and rainfall intensity were somewhat lower, due to difficulty in precise humidity control for such a large sample, and the effect of low water temperature on viscosity and spray cone characteristics. While responses were similar in both test sets, these discrepancies explain small differences in results.

Hydrological response was similar in all initial experiments (Figure 1a). Local runoff generation was almost immediate reflecting high rainfall intensities and susceptibility of the soil to sealing (Slattery and Bryan, 1992b), with discharge at the weir after 5 min of rainfall. In each case virtually the complete flume contributed runoff after about 40 min, but quasi-equilibrium was not reached until 70–115 min due to lagged drainage

(a) (b)

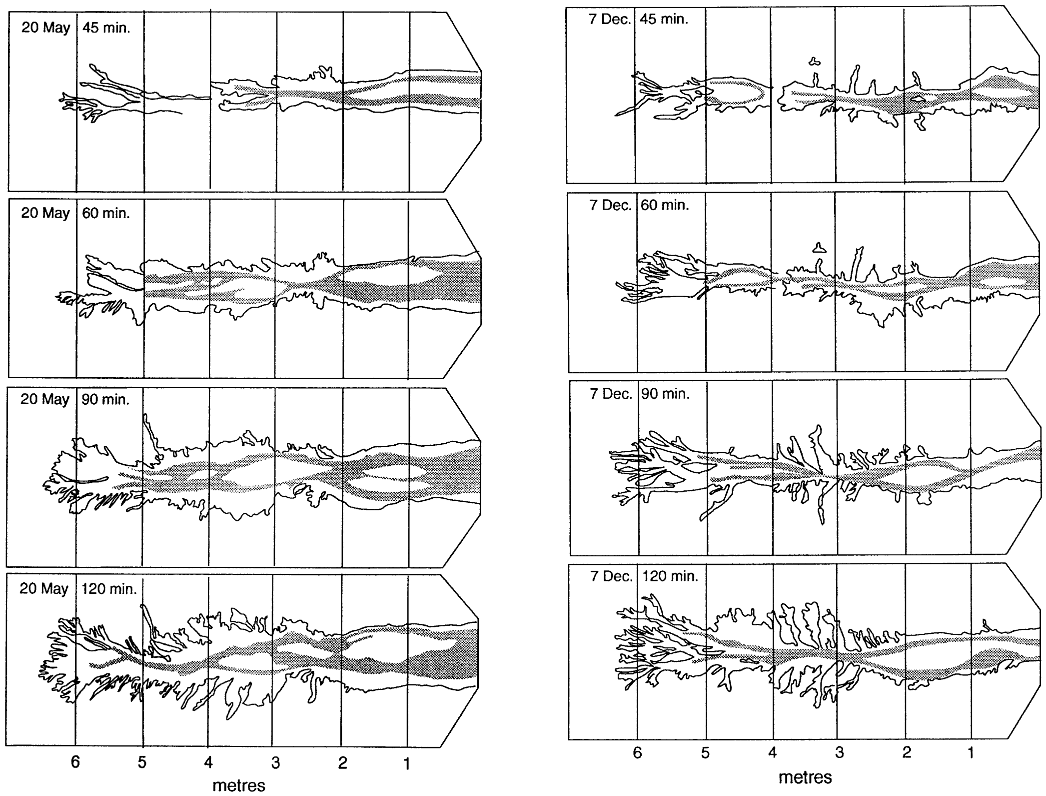


Figure 2. Evolution of rill system during experiment of (a) 20 May; (b) 7 December

system evolution. In subsequent tests on 2 June and 10 December, runoff was virtually instantaneous, with identical runoff coefficients (Figure 1b).

RILL INCISION

Rill incision started at several locations in the central depression within 15–20 min, but a continuous incised channel did not form until nearly 60 min on 6 April and 20 May, and longer on 7 December (Figure 2a, b). Initial rill morphology varied, but on 20 May a distinct arcuate headcut formed 2·5 m above the weir after 16 min. This became pronounced and started to recede rapidly after 26 min. A good photo is not available, but the morphology was identical to examples shown by Bryan (1990, figure 3b) and Slattery and Bryan (1992a, figure 4).

Limited local hydraulic data are available from 6 April, but comprehensive data were collected on 20 May and 7 December (summarized in Table III). Clear differences appear between the upper and lower flume during early stages, and between 20 May and 8 December. Rose (1985) suggested that a critical threshold of ω of 0·5 W m^2 must be reached for rill incision, while Savat (1976), Hodges (1982) and Bryan (1990) all found that standing waves associated with arcuate knickpoint development typically appeared at Fr = 0·6 in shallow flows. Govers (1985) suggested a critical u^* of 0·0354 $m\,s^{-1}$, but Slattery and Bryan (1992a) found 0·056 $m\,s^{-1}$ more appropriate for this soil. On 20 May (Table IIIa) critical threshold values were reached in the lower flume (2–3·5 m) almost at the start of flow. When an arcuate knickpoint formed at minute 16, flow was turbulent (Re > 2000) and all critical values were exceeded. On 7 December similar values were not reached until minute 25, which is consistent with local knickpoint initiation. In the upper flume, flow remained laminar or transitional for much longer, with threshold hydraulic conditions reached only after 42 min on 20 May and 48 min on 7 December.

Table III. Summary hydraulic data and associated rill development features

(a) 20 May experiment

Time (min)	*v*	*q*	*u**	Re	Fr	ff	ω	Flow conditions
Location: 2·0–3·5 m above weir								
0–21	0·140 (0·018)	11·0 (1·29)	0·056 (0·030)	2140 (258)	0·766 (0·124)	1·023 (0·391)	0·460 (0·054)	Sheetwash without incision
21–45	0·145 (0·014)	13·0 (2·14)	0·070 (0·018)	4590 (1739)	0·569 (0·135)	2·525 (1·163)	1·143 (0·516)	Knickpoint incision
45–95	0·305 (0·037)	13·4 (8·67)	0·063 (0·014)	6140 (3328)	1·499 (0·351)	0·326 (0·102)	1·448 (0·826)	Multiple knickpoint incision and pediment development
95–120	0·195 (0·082)	0·76 (0·26)	0·029 (0·001)	598 (472)	2·003 (0·842)	0·256 (0·133)	0·167 (0·070)	Aggradation
Location: 4·5–5·0 m above weir								
0–35	0·075 (0·018)	3·55 (1·43)	0·054 (0·003)	1015 (206)	0·413 (0·066)	4·403 (1·432)	0·224 (0·045)	Sheetwash with limited incision
35–120	0·232 (0·052)	14·48 (4·08)	0·062 (0·003)	4436 (1749)	1·086 (0·226)	0·656 (0·216)	0·996 (0·413)	Knickpoint incision

(b) 7 December experiment

Time (min)	*v*	*q*	*u**	Re	Fr	ff	ω	Flow conditions
0–35	0·164 (0·037)	5·84 (3·84)	0·052 (0·003)	2201 (689)	0·981 (0·201)	0·867 (0·510)	0·492 (0·157)	Sheetwash with very local incision
35–62	0·241 (0·039)	12·09 (4·60)	0·069 (0·006)	5512 (1496)	1·026 (0·161)	0·864 (0·233)	1·298 (0·362)	Knickpoint incision
62–120	0·308 (0·039)	11·08 (3·57)	0·066 (0·004)	6465 (1039)	1·361 (0·195)	0·402 (0·131)	1·565 (0·299)	Multiple knickpoint incision and sapping pediment development
Location: 4·5–5·0 m above weir								
0–55	0·091 (0·038)	2·15 (2·03)	0·036 (0·0101)	711 (679)	0·732 (0·192)	1·776 (1·505)	0·157 (0·152)	Sheetwash with local incision
55–120	0·175 (0·010)	7·34 (2·33)	0·059 (0·006)	2920 (589)	0·875 (0·074)	0·928 (0·162)	0·659 (0·136)	Knickpoint incision

v=velocity (m s^{1}); *q*=discharge (l min^{-1}); *u**=shear velocity (m s^{-1}); Re=Reynolds number; Fr=Froude number; ff=Darcy–Weisbach friction factor; ω= stream power (W m^{-2}). Values in parentheses are standard deviations

Figure 3 shows soil moisture patterns indicated by the TDR probe network. Figure 3a shows the time taken for soil moisture contents to reach 0·25 ml ml^{-1}, a level shown by Slattery and Bryan (1992a) to coincide with rapid decline in shear strength in this soil. Figure 3b shows the time taken to reach positive pore pressures at saturation and to produce significant seepage potential. As the TDR probes integrate soil moisture over the 8 cm probe depth, these data provide a lagged, indirect indication of water table development. Soil moisture evolution is dominated by surface topography and rainfall distribution, but also reflects some local variations in packing density. Wetting occurred most rapidly in the upper flume between 5 and 6 m, where interrill slopes converge to the central depression and rainfall intensities were highest. Because of rainfall distribution the water table developed earlier in the upper flume than on the footslope at the weir. Patterns were similar on 7 December, but were reached more slowly due to lower antecedent soil moisture conditions. The TDR network was insufficiently dense to provide a very detailed indication of water table evolution. However, parallel

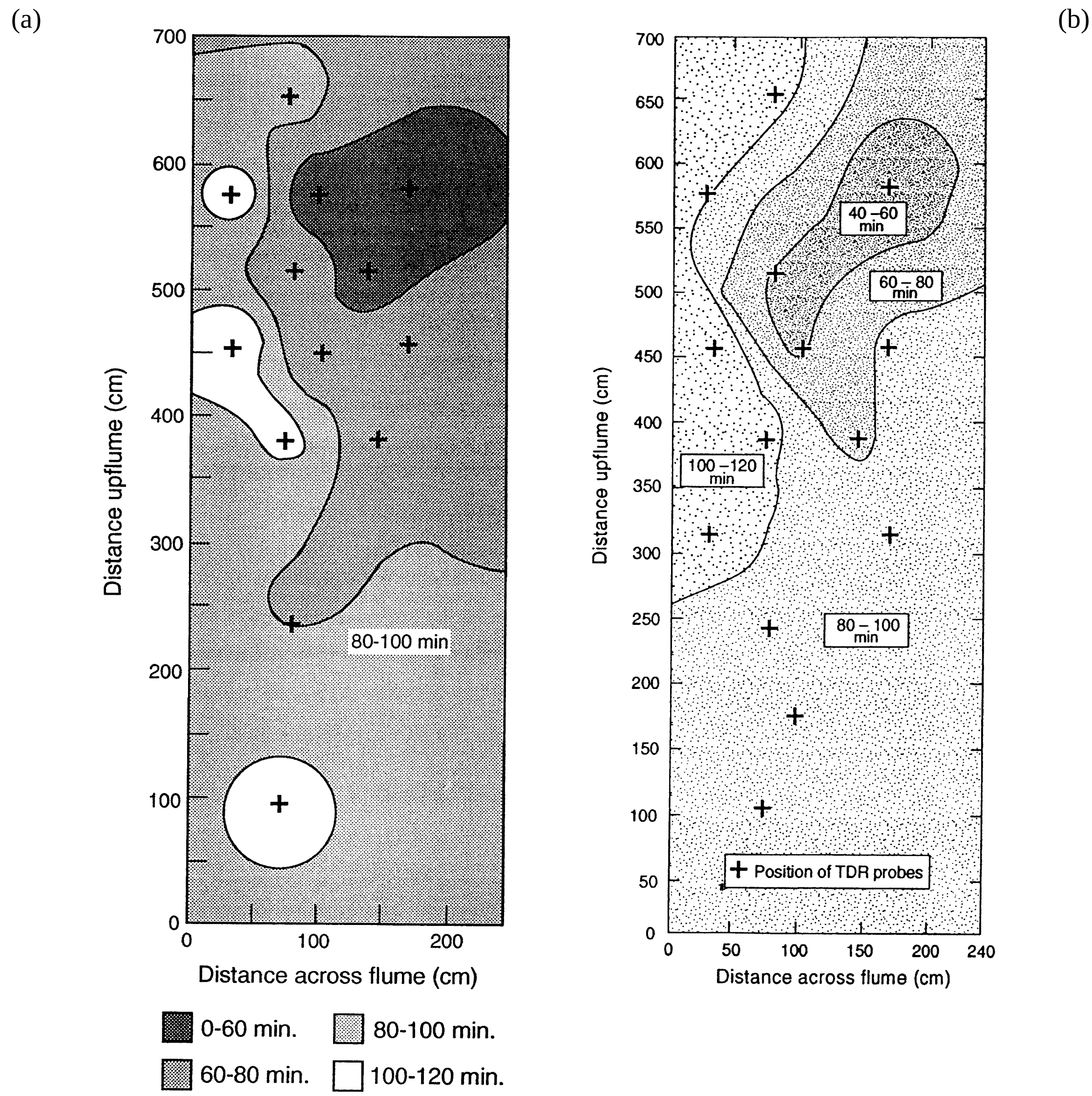


Figure 3. (a) TDR record of time taken for soil to reach volumetric moisture content of $0{\cdot}25\,\mathrm{ml\,ml^{-1}}$. (b) TDR record of time taken for soil to reach saturation during experiment of 20 May

experiments with automated standpipes, microtensiometers and TDR probes (Rockwell, 1995; Hawke, 1997) show complex local variations, strongly influenced by soil moisture ‘fingering’.

The soil moisture patterns show that conditions suitable for sapping were not reached throughout most of the central depression until 60–80 min. The arcuate knickpoints formed in the lower flume on 20 May and 7 December clearly preceded saturation and must be attributed to runoff hydraulic conditions alone, without any sapping contribution. In the upper flume, rill incision started well before critical hydraulic values were reached, at the exact location where saturation levels were first reached (Figure 3b). This is consistent with some influence of subsurface or sapping processes. However, the rills formed were narrow (Figure 2a, b), shallow and had sloping ‘type A’ headcuts (Bryan, 1990), quite unlike the relatively wide, vertical-sided, ‘theatre-headed’ valleys with arcuate headcuts described by Kochel and Piper (1986), for example.

Table IV. Side slope hydraulic data measured during 7 December text

Time (min)	*q*	*u**	τ	Re	Fr	ff	ω
Location: 2.5 m above weir slope = 0·045							
20	0·32	0·015	0·221	38	0·28	4·58	0·004
24	1·42	0·015	0·221	33	0·24	6·97	0·004
56	0·25	0·015	0·221	15	0·11	1·59	0·007
68	0·07	0·015	0·221	55	0·40	1·60	0·006
80	0·06	0·015	0·221	70	0·50	2·24	0·008
97	0·03	0·015	0·221	43	0·31	7·13	0·005
108	0·38	0·015	0·221	92	0·66	3·01	0·010
Location: 5·5–6·5 m above weir: slope = 0·075							
27	0·32	0·019	0·368	70	0·50	4·12	0·013
35	1·42	0·038	1·472	23	0·39	6·97	0·079
82	0·07	0·019	0·368	109	0·81	1·60	0·021
94	0·06	0·019	0·368	92	0·69	2·24	0·017
110	0·03	0·019	0·368	52	0·38	7·13	0·012
118	0·38	0·038	1·472	573	0·59	3·01	0·016

q=discharge ($\mathrm{l\,min^{-1}}$); *u**=shear velocity ($\mathrm{m\,s^{-1}}$); τ=shear stress (Pa); Re=Reynolds number; Fr=Froude number; ff=Darcy–Weisbach friction factor; ω=stream power ($\mathrm{W\,m^{-2}}$)

TRIBUTARY RILL DEVELOPMENT

Because of initial topography, flow concentrated in the central depression, enhancing hydraulic values. A more accurate impression of unbiased rill initiation conditions can be obtained from sheetflow data for the side slopes, where flow lines were not predetermined. Accurate data were difficult to obtain because slopes were short and flows extremely shallow (0·5–1 mm) but satisfactory sets are available for two locations on 7 December (Table IV). Side slopes at the lower location were only 0·5 m long, yielding sheetflow depths estimated at 0·5 mm. At the upper location flow lengths reached up to 1 m with flow depths of 1 mm. Because of the difficulty of measuring such small flow depths, values in Table IV are probably overestimates. Virtually none of the hydraulic variables approached critical values on side slopes (Table IV). Some Fr values indicate possible standing wave development with related bed moulding, which could concentrate flow, but no consistent pattern is apparent. The conclusion is that, in general, threshold hydraulic conditions for rill incision did not occur in side slope sheetflow during initial experiments.

Despite the data reported, tributary rills did form during initial experiments, the pattern for 7 December being lagged and less developed because of lower antecedent soil moisture content (Figure 2a,b). Apart from digitate tributaries in the upper central depression, however, virtually no tributary rills developed during the first 40–50 min (rill-like features between 2 and 3 m at 45 min on 7 December were triggered by dripping off sampling bridges). Rills developed after 40–50 min bore little resemblance to classic branched rill systems described by Horton (1945) and Schumm (1956). Instead, low scarps (ranging in height for 20 May from 0·066 to 0·03 m; mean 0·0148 m) developed along the edge of the central depression, merging into well-defined rill channels in the upper flume. The scarps were initially rather straight, retreating uniformly at about $5\times10^{-5}\,\mathrm{m\,s^{-1}}$, and leaving residual 'pediments' of mean slope 0·034 (2°). Flow across these 'pediments' progressively concentrated into embryo rill channels, localizing headcut retreat, with peak rates reaching $1{\cdot}7\times10^{-4}\,\mathrm{m\,s^{-1}}$. The resulting crenulate scarp morphology is clearly apparent in Figure 4 from the 20 May test.

Side slope hydraulic data (Table IV) show that the miniature scarps, pediments and embryo rill channels described could not have been formed by sheetwash alone. In subsequent tests on 2 June and 10 December with higher antecedent moisture and considerably greater flow discharges, critical hydraulic values were reached only locally on a few interrill slopes in the upper flume, and mean interrill hydraulic conditions were well below threshold values (Table Va). Even in concentrated flow in embryo rills, hydraulic values barely reached threshold values (Table Vb).

Hydraulic conditions eliminate the possibility of scarp initiation by surface flow alone, but their development does coincide in time and location with soil moisture contents approaching saturation. Sapping

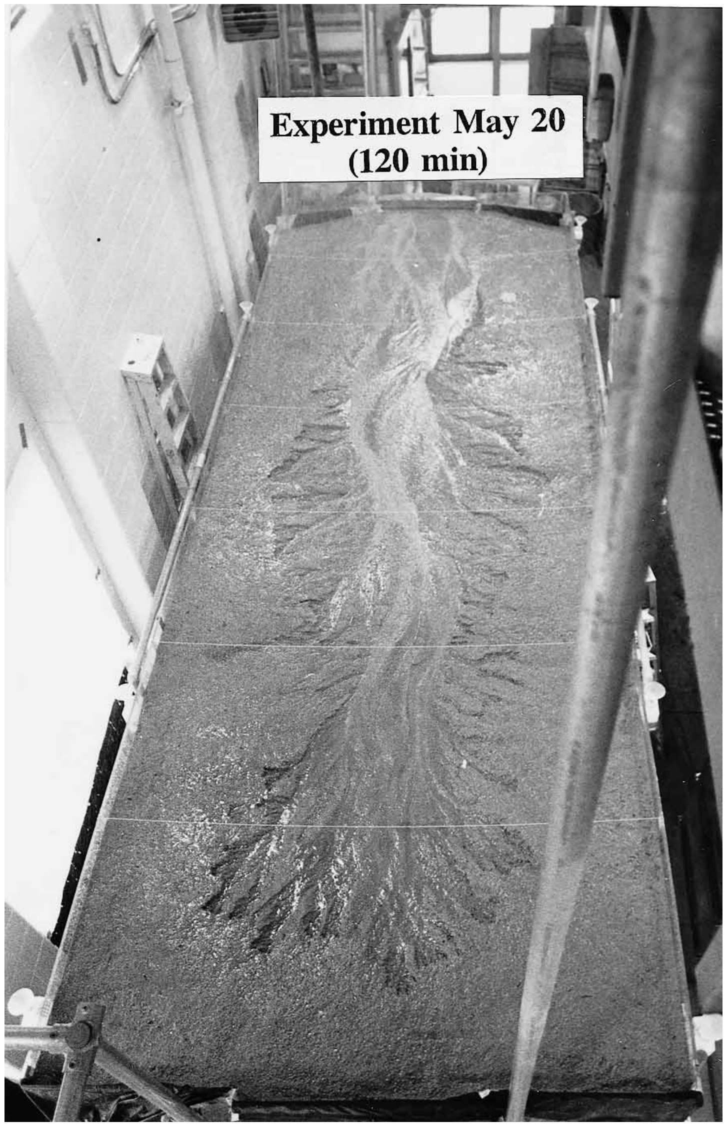


Figure 4. Rill system development at the end of 120 min experiment on 20 May

therefore appears to be a potential process in scarp development. Scarp formation also coincided with significant increase in sediment concentration at the weir, particularly on 7 December. Weir sediment discharge was strongly correlated with scarp length measured at the four time intervals shown in Figure 1, ($r = 0{\cdot}94$ and $0{\cdot}98$ for 20 May and 7 December, respectively; both significant at the 1 per cent level).

The character of the microscarps, pediments and microrills at the end of a 120 min experiment is quite well-shown for 7 December in Figure 5, though the pediment was broader and more uniform on 20 May (Figure 4). The air photo record was adequate to produce the maps shown in Figure 2, but detailed morphological measurements could not be taken during experiments without major interference with active processes. Several indices of basin and channel morphometry were measured for the embryo rills shown in Figure 5, for the initial 'knickpoint' channels formed in the mid-lower flume (before saturation) and for the digitate rills formed in the upper flume (after saturation). These are shown in Table VI, with comparable data for 'theatre-headed' valleys on the Colorado Plateau (Laity and Malin, 1985), for Martian valleys (Kochel and Piper, 1986), and for the sapped drainage network described by Gomez and Mullen (1992). The embryo rills shown in Figure 5 also resemble the beach features described by Higgins (1982) for which no data are available.

Table V. Hydraulic data measured during subsequent experiments on 2 June and 10 December

(a) Interill slopes

	v	*q*	*u**	τ	Re	Fr	ff	ω
10 December (*n*=24)								
Mean	0·037	0·293	0·025	0·069	152	0·374	5·333	0·025
Std. dev.	0·012	0·144	0·008	0·046	57·8	0·125	5·013	0·018
Max. value	0·063	0·560	0·036	0·130	303	0·644	19·787	0·074
2 June (*n*=16)								
Mean	0·036	0·295	0·048	2·344	179	0·339	19·604	0·122
Std. dev.	0·012	0·182	0·008	0·836	100	0·114	14·833	0·146
Max. value	0·061	0·870	0·069	4·730	469	0·564	61·143	0·650

(a) Interill slopes

	v	*q*	*u**	τ	Re	Fr	ff	ω
10 December (*n*=39)								
Mean	0·075	0·754	0·047	0·238	685	0·576	4·165	0·201
Std. dev.	0·024	0·593	0·013	0·120	405	0·264	3·581	0·121
Max. value	0·125	1·940	0·066	0·430	1469	1·369	15·037	0·419
2 June (*n*=23)								
Mean	0·069	0·375	0·056	3·220	546	0·500	15·018	0·255
Std. dev.	0·029	0·226	0·009	1·083	287	0·208	32·310	0·142
Max. value	0·141	0·850	0·076	5·730	1154	1·051	154·544	0·607

v=velocity ($m\,s^{-1}$); *q*=discharge ($l\,min^{-1}$); *u**=shear velocity ($m\,s^{-1}$); τ=shear stress (Pa); Re=Reynolds number; Fr=Froude number; ff=Darcy–Weisbach friction factor; ω=stream power ($W\,m^{-2}$)

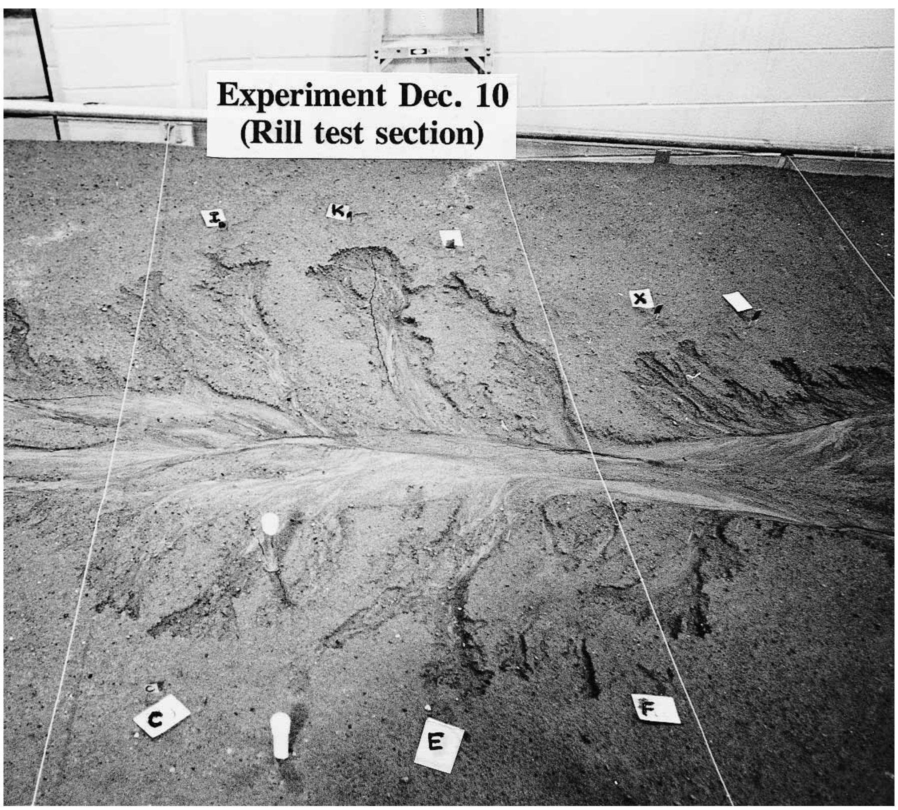


Figure 5. Characteristics of rill system and locations of detailed hydraulic monitoring at start of 10 December experiment

Table VI. Comparison of morphometric indices for drainage basins attributed to surface flow, subsurface processes or some combination

Surface flow	*P* (m)	*L* (m)	*A* (m^2)	*K*	*L/W*	*F*	*C*
20 May (45 min) (lower)	9·04	2·85	2·84	0·72	4·75	0·35	0·44
7 December (45 min) (lower)	8·77	2·74	2·28	0·83	6·00	0·30	0·37
Subsurface processes							
Gomez and Mullen (1992) (360 min)	5·33	1·09	0·33	0·90	1·66	0·28	0·15
Gomez and Mullen (1992) (2160 min)	8·56	1·47	0·99	0·54	1·23	0·46	0·17
20 May (45 min) (upper)	9·88	1·58	0·035	1·96	5·33	0·14	0·045
7 December (45 min) (upper)	7·49	1·51	0·030	1·87	3·84	0·13	0·068
Colorado Plateau (Laity and Malin, 1985)	1·81 (km)	5·74 (km^2)	3·23 (km^2)	2·56	4·19	0·10	12·39
Colorado Plateau (Laity and Malin, 1985)	1·19 (km)	3·87 (km^2)	1·58 (km^2)	2·37	3·76	0·11	13·92
	1·23 (km)	3·23 (km^2)	1·08 2·42	1·88	0·10	8·98	
Mars (Kochel and Piper, 1986)			603 (km^2)	2·33			
Mixed processes							
10 December rills	1·69	0·59	0·005	1·55	3·50	0·28	0·25
2	2·19	0·59	0·010	0·87	2·03	0·28	0·26
3	1·69	0·63	0·005	1·83	3·86	0·14	0·24
4	1·44	0·46	0·005	1·04	2·95	0·24	0·30
5	2·06	0·56	0·010	0·80	2·85	0·31	0·29
6	1·19	0·43	0·003	1·40	3·43	0·18	0·30

P=perimeter; *L*=max. length; *A*=area; *K*=Lemniscate *K* (Chorley *et al.*, 1957); *L/W*=length:width; *F*=form factor (Horton, 1932); *C*=Basin circularity (Miller, 1953)

DISCUSSION

Detailed experimental response patterns are complex, but three general features are apparent.

1. Hydraulic conditions in most parts of the flume during the experiments did not reach threshold values generally identified as necessary for rill initiation. Exceptions were the lower part of the central depression and the uppermost section of the flume where interrill slope angles, and therefore shear velocities, were higher. When entrainment occurred in other locations, either subsurface processes were involved, or the threshold hydraulic values previously confirmed for the test soils do not apply.
2. Increase in sediment discharge at the weir closely coincided with incipient soil saturation and development of miniature scarps. This supports the critical role of soil moisture and subsurface processes in rill system evolution in these experiments.
3. The data in Table VI indicate that it is not possible to distinguish the results of surface and subsurface erosion processes at rill scale by common morphometric indices. The 'theatre-headed' valleys of the Colorado Plateau, at much larger scale, do appear morphologically distinct, and agree with available data for Martian valleys. This indicates that controls on large-scale sapping erosional processes engendered by seepage pressures in bed-rock differ from those active at rill scale in soils.

Soil moisture can influence many physical and physico-chemical processes active in soils at rill scale. Analysis is complicated by confusing, ill-defined terminology (discussed in detail by Howard and McLane (1988) and Dunne (1990)). However, two processes are particularly relevant for these experiments: (1) seepage erosion in which particles are entrained or ejected by a critical drag force induced by water seeping through soil pores; this may result in either localized spring sapping or a more extensive sapping line, depending on internal

soil structure (Dunne, 1990); (2) reduction in soil shear strength, with increased vulnerability to entrainment by either surface or concentrated subsurface flow.

The evolution of soil moisture patterns (Figure 3a,b) and the water table are critical in isolating the processes active in rill system evolution. Water table development was complex, with much local variation, but conditions were not generally suitable for subsurface flow before saturation in the upper flume (Figure 3b). Rill initiation occurred with knickpoint scour in the central flume, 2–3·5 m above the weir, after 16–25 min. This preceded saturation at this location, and probably also water table development. No TDR probes were situated at this point but calculations from rainfall rates, infiltration rates, bulk density and hydraulic conductivity, corrected for hydraulic compaction, show that a water table would have started to form after 27 min, and saturation could not have occurred here before minute 59 on 20 May and minute 33 on 7 December. Knickpoint scour at this location must therefore be attributed entirely to runoff tractive forces. In the upper flume, saturation occurred earlier and rills developed before threshold hydraulic values were reached. In both cases, entrainment was enhanced by soil strength decline once moisture content exceeded 0·23–0·25 ml ml^{-1}. Discharge and sediment concentration data at the weir (Figure 1a,b) show that flow transport capacity was more than adequate to remove all sediment entrained at this stage.

Initial knickpoint scour expanded to a true rill by headward retreat with some channel widening by bank scour, but no bank collapse. Using the Terzaghi (1943) expression for critical vertical bank height:

$$H_c = \frac{4c}{y}$$

(where c = cohesive strength, y = bulk unit soil weight), with shear strength data from Slattery and Bryan (1992a), gave a critical incision depth of 28 m. Initial knickpoint incision in the central flume was only 0·03 m. Critical incision depth declines swiftly with increasing moisture content, as shear strength trends towards zero at the saturation volumetric moisture content of 42 per cent (Slattery and Bryan, 1992a). Direct shear strength measurement with a miniature shear vane during the 10 December test gave mean and minimum shear strength values of 0·0302 kPa and 0·006 kPa respectively at saturation. Calculated critical incision depth declined to 0·06 m at saturation. This indicates that bank collapse did not contribute to channel widening in the central flume, but did play a role in the upper flume where central rill incision eventually reached 0·11 m.

The separate rill systems in the central and upper flume joined at about the same time that saturation occurred in much of the upper flume (Figure 3b). Although saturation was incomplete, a more or less continuous water table probably covered most of the flume by this stage. The central rill subsequently widened and residual pediments and microscarps developed, coinciding with abrupt increase in sediment discharge at the weir (Figure 1a,b).

To isolate the processes involved in microscarp and pediment development, it is necessary to consider potential seepage forces along central rill banks. Iverson and Major (1986), Kochel *et al*. (1985), Howard and McLane (1988) and Dunne (1990) provide good theoretical discussions of the components involved. The precise time of initiation varied along the central rill, but was clearly apparent at 3·5 m above the weir after 45–50 min. The basic morphology and dimensions of the rill–pediment–microscarp transition at this time and location are shown in Figure 6. Water table slope is critical in determination of flow lines and seepage forces. This could not be determined with available instruments, but at 45–50 min must have been very close to zero. Calculations from infiltration rate, saturated hydraulic conductivity (k) and porosity indicate a water table slope of approximately 0·024 after 120 min. The relatively high k value of $2{\cdot}2\times10^{-4}$ m s^{-1} would have produced some drainage near the rill wall apex, but the precise point of water table intersection on the rill wall is uncertain. Observations from other experiments suggest that it was about 0·02 m above the rill water level, as shown in Figure 6.

The seepage velocities based on measured k and the calculated final hydraulic gradient (0·024) are around $5{\cdot}3\times10^{-5}$ m s^{-1}. Such velocities are too small to cause sapping and particle ejection. Even marked increase in water table slope close to the rill wall would not greatly increase seepage velocities or pressures. Positive pore pressures and reduced shear strength would, however, increase the effective erosivity of interrill flow, causing localized undercutting. The resulting undercut vertical 0·02 m high microscarp is below the critical height, even

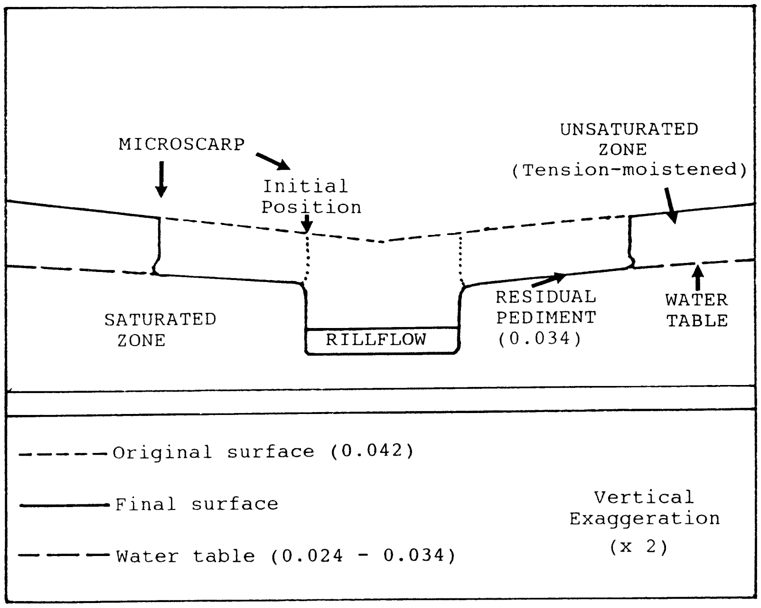


Figure 6. Schematic diagram showing flume conditions at 3·5 m above the weir shortly after rill initiation, and at the end of experiment on 20 May

when saturated. The initial surface strength was also increased slightly by rainsplash sealing and compaction (Slattery and Bryan, 1992b, 1994). Soil strength was sufficient to prevent mass scarp failure, but continual undercutting and particle removal caused progressive microscarp retreat.

The development sequence outlined is based on observation, calculation and some assumptions. The results are, however, consistent with the observed microscarp and pediment morphology and development rate. After initiation, microscarps retreated at an average rate of 5×10^{-5} m s^{-1}, producing a maximum final pediment width of 0·64 m. Calculations with undercutting concentrated 0·02 m above the rill surface and mean pediment and initial surface slope angles of 0·034 and 0·042 respectively yield a predicted microscarp height of 0·025 m at pediment width of 0·64 m. The actual average microscarp height measured was 0·0148 m, with a range from 0·006 to 0·03 m.

Evolution of the rill system by microscarp retreat due to undercutting concentrated above the rill channel bed, agrees with observed pediment morphology. Without precise information about local rill flow conditions, it is not certain why undercutting is concentrated at this point, rather than the base of the rill wall. The precise balance of stresses in rill flow will also depend on channel meandering and bed form. The most likely explanation appears to be that the rill channel had already reached a stable width with approximate equilibrium discharge. Certainly no significant subsequent widening of the central rill channel occurred in any experiment.

Micropediment slope angle (mean: 0·034) must reflect the minimum threshold necessary to transport material from the retreating microscarp to the rill channel. It is clear from direct observation during the 10 December test, which showed no deposition or scour on the pediment, and from hydraulic conditions, that the pediments are essentially transport surfaces, not sources of significant entrainment. Flow is extremely shallow (0·5–1 mm) and mean u^* values (0·016 m s^{-1}) are well below the entrainment threshold. Pediment sheetflow was laminar, with a mean Re of 143, though flow was disturbed by rainsplash. Laminar conditions would have been enhanced by the emergence of low velocity seepage. This would help to protect the pediment surface from entrainment by rainsplash while enhancing sheetflow discharge and transportation capacity. The angle of the pediment transport slope is therefore probably slightly lower than it would be without seepage.

Concentrated flow, up to 1·5 mm deep, occurred in microrills crossing the pediment. These alway matched zones of flow concentration on interrills, and points of maximum retreat rates along crenulate microscarps. Some entrainment might have occurred in these concentrations, with u^* reaching 0·05 m s^{-1}, but incision was

hardly measurable, and not sufficient to cause significant subsurface flow diversion on the saturated pediment. Differential microscarp retreat concentrated at microrills would, however, have progressively deflected flowlines. This was particularly notable after the 7 December test, where portions of the original interrill surface were isolated by intersection of adjacent microrill headcuts (Figure 5).

Analysis of experimental results indicates that surface flow concentration is the dominant factor determining rill initiation and location. The precise form and evolution of the rill system is, however, strongly influenced by soil moisture patterns. Data are not sufficiently precise to eliminate the possibility of localized sapping, but they do indicate that the most important effect of soil saturation in these experiments was significant reduction in soil shear strength and the threshold flow shear stress necessary for particle entrainment. The conspicuous microscarp and pediment morphology developed in initial experiments resulted from differences in strength between the saturated lower layers and the undersaturated surface. This indicates that the actual final water table slope in initial experiments was probably closer to the mean pediment angle of 0·034, than the calculated value of 0·024. Increase in surface strength due to rainsplash sealing and compaction does not appear to have significantly increased microscarp stability; on 2 June and 10 December, when the water table reached interrill surfaces, microscarps were virtually eliminated.

CONCLUSIONS

Despite small variations in some experimental conditions, the pattern of rill evolution was essentially similar in the three initial experiments. In each case rills initiated by local scour in the central depression, but a fully integrated rill system did not appear until much of the flume area approached saturation. At this stage microscarps developed along the central trunk rill walls. These retreated progressively into interrill surfaces, leaving residual low-angle pediments. Microscarp initiation coincided with rapid increase in sediment discharge, and the increasing scarp perimeter length was closely correlated with weir sediment yield. Microscarps were markedly crenulate with maximum retreat rates at points where microrill discharge from initial interrill surfaces concentrated scarp erosion.

Initial scour and rill incision in the central depression was associated with hydraulic values above commonly identified thresholds and clearly preceded soil saturation. Similar hydraulic values were only very sporadically reached elsewhere on the flume. Tributary microrill incision, and microscarp and pediment development were all closely linked to high soil moisture levels, and water table evolution. Some sapping influence on microscarp initiation cannot be categorically ruled out, but small hydraulic gradients and measured saturated hydraulic conductivities indicate that seepage forces were minimal. The dominant impact of saturation was to reduce soil shear strength to near zero, permitting significant entrainment by runoff well below normal thresholds. Vertical microscarps survived because of the slightly higher strength of the uppermost unsaturated soil layer. Microscarp retreat involved undercutting of this layer along the water table and transport across the residual pediment to the central rill. The pediment is interpreted as essentially a transport slope, where entrainment is limited and transportation enhanced by emerging low velocity laminar seepage.

Virtually all the morphologic features of the evolving rill system were strongly influenced by both surface and subsurface processes, reflecting local soil moisture conditions. None of the morphometric indices measured could be linked solely to either category of process with any confidence. We conclude, therefore, that rill morphology is not a reliable indicator of the dominance of surface or subsurface erosion. Although the tests involved extreme rainfall, all other conditions occur frequently on agricultural fields, and are by no means uncommon on natural hillslopes. The evolution of a shallow water table, as observed in these experiments, perched on a plough pan, soil horizon or rock surface of low permeability, must be frequent, particularly during wet winters. While rill incision solely controlled by surface erosion, or by subsurface erosion (as in the case of micropiped smectite clays in badlands), is incontrovertible, the intimate interaction of both sets of processes, as observed in these experiments, is probably much more common.

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